

LETTER TO THE EDITOR

# Planck revealed bulk motion of Centaurus A lobes

F. De Paolis<sup>1,2</sup>, V.G. Gurzadyan<sup>3</sup>, A.A. Nucita<sup>1,2</sup>, G. Ingrosso<sup>1,2</sup>, A.L. Kashin<sup>3</sup>, H.G. Khachatryan<sup>3</sup>, S. Mirzoyan<sup>3</sup>, G. Yegorian<sup>3</sup>, Ph. Jetzer<sup>4</sup>, A. Qadir<sup>5</sup> and D. Vetrugno<sup>6</sup>

<sup>1</sup> Dipartimento di Matematica e Fisica “E. De Giorgi”, Università del Salento, Via per Arnesano, I-73100, Lecce, Italy

<sup>2</sup> INFN, Sez. di Lecce, Via per Arnesano, I-73100, Lecce, Italy

<sup>3</sup> Center for Cosmology and Astrophysics, Alikhanian National Laboratory and Yerevan State University, Yerevan, Armenia

<sup>4</sup> Physik-Institut, Universität Zürich, Winterthurerstrasse 190, 8057 Zürich, Switzerland

<sup>5</sup> School of Natural Sciences, National University of Sciences and Technology, Islamabad, Pakistan

<sup>6</sup> Department of Physics, University of Trento, I-38123 Povo, Trento, Italy and TIFPA/INFN, I-38123 Povo, Italy

Submitted: XXX; Accepted: XXX

## ABSTRACT

Planck data towards the active galaxy Centaurus A are analyzed in the 70, 100 and 143 GHz bands. We find a temperature asymmetry of the northern radio lobe with respect to the southern one that clearly extends at least up to  $5^\circ$  from the Cen A center and diminishes towards the outer regions of the lobes. That transparent parameter - the temperature asymmetry - thus has to carry a principal information, i.e. indication on the line-of-sight bulk motion of the lobes, while the increase of that asymmetry at smaller radii reveals the differential dynamics of the lobes as expected at ejections from the center.

**Key words.** Galaxies: general – Galaxies: individual (Cen A) – Galaxies: halos

## 1. Introduction

Centaurus A (and its parent galaxy NGC 5128) is a radio galaxy and represents the closest AGN to us, being at a distance of  $3.8 \pm 0.1$  Mpc (Harris et al. 2010). Its jet is clearly visible both in radio and X-rays<sup>1</sup> and since its discovery (Bolton 1948) Cen A has been extensively studied over the entire range of the electromagnetic spectrum (for a review see Israel 1998) with a sensitivity and spatial resolution impossible for other active galaxies. It is an extended, morphologically complex (a detailed description of the radio morphology may be found a.g. in Burns et al. 1983; Meier et al. 1989) and fairly symmetric source exhibiting two giant lobes: the northern one (GLN) and the southern one (GLS), spanning in declination between approximately  $-38^\circ$  and  $-48^\circ$  (the coordinates of the Cen A center are R.A. (J2000) =  $13^h25^m27.6152^s$ , Dec. (J2000) =  $-43^\circ0.1'08.805''$ ). We note that an angle of about  $10^\circ$  on the sky means a physical size at the Cen A distance of  $\simeq 600$  kpc in projection and that the redshift of Cen A is  $z=0.01825$ , corresponding to a recession velocity of about  $540 \text{ km s}^{-1}$ .

The elliptical (S0) galaxy NGC 5128 is an example of the family of ellipticals that have an absorbing band of gas and dust projected across the stellar body. The center of this system harbors a supermassive black hole with mass about  $10^7 - 10^8 M_\odot$  (see e.g. Silge et al. 2005; Marconi et

al. 2006; Neumayer 2010) which powers two jets, two inner lobes (with size about a few arcmin each) and the two outer giant lobes as well. The GLN and the northern jet are likely tilted towards the observer and the GLN is thought to be closer to us than the GLS. Indeed, the jets appear clearly in the radio band and are obviously shooting out of Centaurus A, with the radio emission becoming more diffuse at greater distances from the center of the galaxy. The jets consist of a plasma state, i.e. a high-temperature stream of matter. The jets are also clearly observed in X-rays (see e.g. Karovska et al. 2002 and references therein). The most prominent feature is the jet extending for about 8 kpc towards the northeast (upper left in the sky) while a less prominent jet extends towards the southwest. The apparent brightness difference between the jets and the proper motion asymmetries of both the jets and the inner lobes (Tingay et al. 2001) are thought to be due to the viewing geometry: the first jet is moving towards us, while the second is moving away (see e.g. Burns et al. 1983 and Israel 1998). This was also suggested by the Faraday depolarization analysis of the southern inner lobe (Clarke et al. 1992).

Motivated by the discussion above and by the unique tool that is provided by data in the microwave region of the electromagnetic spectrum to probe the large-scale temperature asymmetries towards nearby astronomical systems, in this Letter we study the Cen A system by using *Planck* data following the same approach adopted in De Paolis et al. (2011, 2014) for the M31 galaxy.

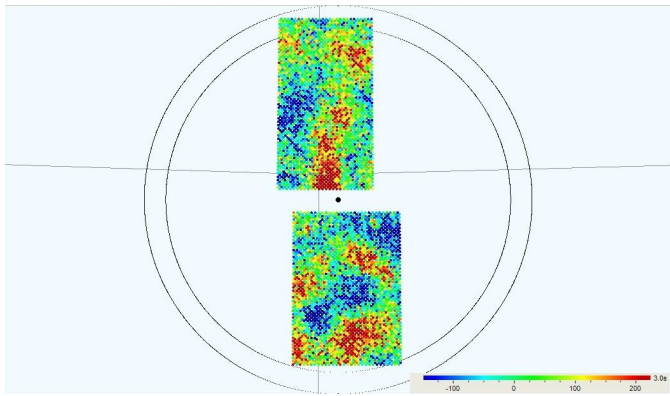
Send offprint requests to: F. De Paolis, e-mail: francesco.depaolis@le.infn.it

<sup>1</sup> In the radio band it is classified as a Fanaroff-Riley type I low luminosity radio galaxy, as a Seyfert 2 object in the visible and a “misdirected” BL Lac type AGN at high-energy.

## 2. Planck data analysis and results

We have considered *Planck* 2015 release data (Planck Collaboration I 2015) in the bands at 70 GHz detected by the LFI instrument, and in the bands at 100 and 143 GHz detected by the HFI instrument (for a review on *Planck* results and instruments characteristics we refer to e.g. Burigana et al. 2013). The resolution in these *Planck* bands are  $13'$ ,  $9.6'$  and  $7.1'$  (in terms of FWHM) at 70, 100 and 143 GHz, respectively, and  $N_{side}=2048$  for CMB temperature (Planck Collaboration XVI 2015). The sensitivity, angular resolution and frequency coverage of *Planck* make it a powerful instrument for cosmology as well as galactic and extragalactic astrophysics (Planck Collaboration I 2015). In order to reveal and study the Cen A giant lobes GLN and GLS in microwaves we have divided the Cen A sky field in two parts as shown in Fig. 1 removing the innermost part (about  $20'$ ) of Cen A corresponding to the NGC 5128 galaxy and the innermost radio lobes.

The mean temperature excess  $T_m$  in  $\mu K$  in each region was obtained in each *Planck* band at 70, 100 and 143 GHz with the corresponding standard error <sup>2</sup>.

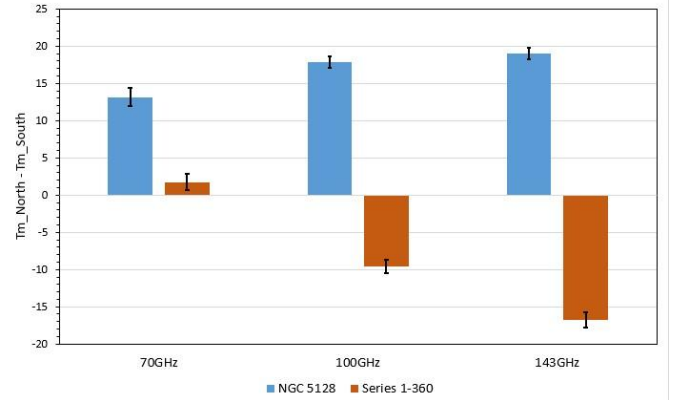


**Fig. 1.** The *Planck* fields towards Cen A galaxy in which our analysis is performed are shown. The radius of the outer circle is of  $5^\circ$  about the NGC 5128 center (with Galactic coordinates  $l=309.52^\circ$ ,  $b=19.42^\circ$ ). The northern field (with 10792 pixels), corresponding to the GLN radio lobe, has Galactic coordinates  $308.65^\circ \leq l \leq 311.03$  and  $19.64^\circ \leq b \leq 23.92^\circ$  while those of the southern field (which has 11011 pixels), corresponding to the GLS, are  $307.98^\circ \leq l \leq 310.64$  and  $15.58^\circ \leq b \leq 19.14^\circ$ .

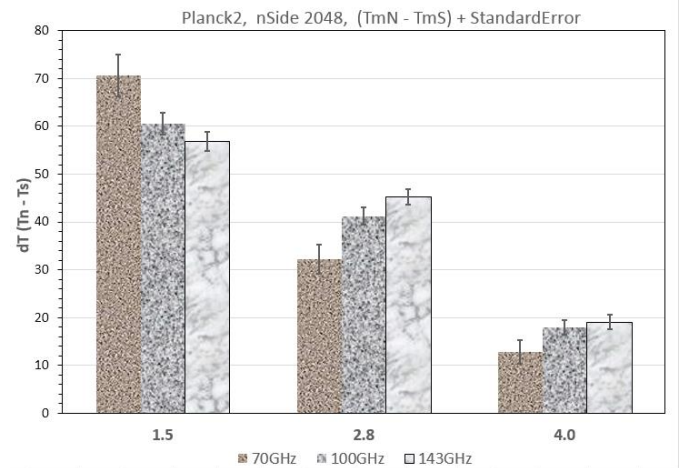
The results obtained for the temperature difference between the GLN and the GLS temperature in each of the three *Planck* bands are shown in Fig. 2. As one can see (in blue), the GLN region is hotter than the GLS region by about  $13 \mu K$  at 70 GHz,  $17 \mu K$  at 100 GHz and  $20 \mu K$  at 143 GHz (in blue in the histogram). This results, most likely, from a Doppler-induced effect related to the bulk velocity of the jet powering the Cen A radio lobes and/or to their rotation with respect to an axis directed along the East-West direction.

To test whether the temperature asymmetry we see is real or can be explained as a random fluctuation of the

<sup>2</sup> The standard error has been calculated as the standard deviation of the excess temperature distribution divided by the square root of the pixel number in each region. We have verified that within the errors, the sigma values calculated in that way are consistent with those evaluated by using the covariance matrix obtained by a best-fitting procedure with a Gaussian to the same distribution.



**Fig. 2.** The excess temperature in  $\mu K$  (in blue) of the northern Cen A lobe with respect to the southern one are given in the 70 GHz, 100 GHz and 143 GHz *Planck* data. In brown we give the temperature excess of 360 control regions equally spaced at one degree distance to each other in Galactic longitude and at the same latitude as NGC 5128. The standard errors are also shown.



**Fig. 3.** The excess temperature in  $\mu K$  (with the standard errors) of the northern Cen A lobe with respect to the southern one are given in the 70 GHz, 100 GHz and 143 GHz *Planck* data up to  $1.5^\circ$  ( $\simeq 92$  kpc),  $2.8^\circ$  ( $\simeq 171$  kpc) and  $4.0^\circ$  ( $\simeq 245$  kpc) from the galaxy center.

CMB signal (which is very patchy) we consider 360 control field regions with the same shape as the GLN and GLS regions and at the same latitude, but at  $1^\circ$  longitude from each other. For each region we determined the excess temperature profile and calculated the average profile and corresponding standard deviation. The results obtained are shown in brown in the histogram in Fig. 2. As one can see, the temperature asymmetry in the 360 control fields at 100 and 143 GHz is the opposite of that towards Cen A with the southern field generally hotter than the northern one (in the 70 GHz band the temperature asymmetry of the control fields is substantially smaller with respect to that towards the Cen A lobes). This trend for the 360 control fields is easily understandable, since the Galactic latitude of the southern lobes is  $14 - 19^\circ$  (the center of Cen A is at latitude  $b = 19.473^\circ$ ) and at these latitudes the foregrounds due to our Galactic disk is non-negligible. Indeed, since the Cen A giant lobes happen to be aligned in the sky almost

orthogonal to the Milky Way, the southern lobe has to be more contaminated by the disk's radiation than the northern one. We also stress that the procedure we followed to test the observed effect, that is of considering the 360 control regions, is more reliable than simulating the CMB sky maps in each band considered. While the latter methodology of generating sky maps to estimate the error bars is mandatory dealing with the whole sky (as in cosmological studies), in our case we are considering only rather small regions of the *Planck* sky maps and the adopted procedure is more reliable since it avoids the simulation ambiguities.

In Fig. 3 the analysis of the temperature asymmetry between the GLN and GLS of Cen A within three different galactocentric radii ( $1.5^\circ$ ,  $2.8^\circ$  and  $4.0^\circ$ , corresponding to about 92 kpc, 171 kpc and 245 kpc, respectively) is presented. It is clear that the temperature asymmetry diminishes as increasing the field region area. The radial dependence of the temperature asymmetry in the three *Planck* bands considered might be indicative of different emission mechanisms in the microwaves at different galactocentric distances, even if the quality of the present data cannot allow us to draw a definitive conclusion in this respect.

### 3. Conclusions

As discussed in the previous section, we have considered *Planck* 2015 release data in the bands at 70, 100 and 143 GHz and detected a temperature asymmetry between the GLN and the GLS of the Cen A system. Notice that no detection of the Cen A giant lobes was present until now in the microwaves at wavelengths higher than 60 GHz (Hardcastle et al. 2009). In particular, the GLN appears substantially hotter than the GLS up to a galactocentric distance of about  $5^\circ$ . The temperature asymmetry is present in all the bands considered and decreases from the innermost region (being about 70  $\mu$ K at 70 GHz within  $1.5^\circ$  from the Cen A center) to about 14  $\mu$ K at 70 GHz within  $4^\circ$  from the galaxy center. What we find seems to confirm what is known from radio observations about the emission direction and motion of the Cen A jet and inner northern and southern lobes.

Since the Cen A giant lobes happen to be aligned in the sky almost orthogonal to the Galactic disk, as mentioned, the southern lobe has to be more contaminated by the disk's radiation than the northern one, giving an effect opposite to that observed towards the Cen A lobes. This fact is reflected in the behavior of the mean temperature asymmetry, including the band dependence, of the 360 control regions. Hence, in view of Galactic contamination, the genuine Cen A temperature contrast has to be even stronger. Moreover, since we are not dealing with the absolute but with the mean temperature differences only, the role of the various noise sources is vanishing. This is similar to the case of the CMB dipole, where the temperature difference indicates the motion of the observer.

In general, the observation of the Cen A temperature asymmetry may be explained by one (or more) of the following astrophysical emission mechanisms: (i) free-free emission, (ii) synchrotron emission, (iii) anomalous microwave emission (AME) from dust grains, (iv) the kinetic Sunyaev-Zel'dovich (SZ) effect, and (v) cold gas clouds populating the outer regions of Cen A (as first proposed, in the context of the M31 halo, by De Paolis et al. 1995). A detailed study of what each of these five possible causes might con-

tribute, using all the *Planck* bands to constrain the model parameters and the relative weight of these five models, will be published elsewhere. Here, we only note that effects (i) – (iii) are strongly wavelength dependent at microwave frequencies (see, e.g. Bennett (2003); Planck Collaboration XII (2013), while (iv) and (v) are almost independent of the observation band in the microwave regime. AME (item iii) has been observed in various interstellar environments, in particular in the diffuse ISM (Miville-Deschênes et al. 2008) and in dark clouds (Watson et al. 2005), and might play a role also in galactic halo environments, provided dust grains are present.<sup>3</sup>

As a matter of fact, and irrespective of the physical emission mechanisms, the detected mean temperature asymmetry has to indicate the line-of-sight motion of the lobes.

In the viewing geometry, a GLN hotter than the GLS will be due to the direction of the powering jets, as also suggested by observations in other wavelengths (see e.g. the discussion in the Introduction), also a Doppler induced effect due to the rotation of the giant radio lobes with respect to an axis directed along the East-West direction would contribute, an effect similar to that observed towards the halo of the M31 galaxy (De Paolis et al. 2011, 2014). Although the resolution of this issue is not the aim of the present Letter, we shall give some possible hints in the following. The rotation of NGC 5128 and its halo has been investigated by studying the velocity distribution of more than 400 planetary nebulae within a galactocentric distance of about  $20'$  ( $\simeq 20$  kpc). In particular, Hui et al. (1995) found that the NGC 5128 rotation axis is offset from its photometric minor axis by about  $39^\circ$ . It was also found that the planetary nebulae ordered motions become more important with respect to their random motions at larger galactocentric radii, with the rotation component reaching about 100  $\text{km s}^{-1}$  and 50  $\text{km s}^{-1}$  along the photometric major and minor axes, respectively.

The kinematics of the globular clusters around Cen A gives a similar indication, in particular with the metal rich ones showing both major and minor axis rotation (Hui et al. 1995). This was also confirmed by a more recent analysis by Woodley et al. (2010) who considered a sample of 605 globular clusters extending up to a galactocentric distance of about  $45'$ . It was found that the metal rich globular clusters are rotating with an ordered speed of 43  $\text{km s}^{-1}$  while the metal poor ones have a very mild rotation signature of  $\simeq 26 \text{ km s}^{-1}$ . We have independently analyzed the radial velocity measured in the globular cluster sample in Woodley et al. (2010) and Peng et al. (2004) and, after removing the innermost globular clusters (within a galactocentric radius of about  $4'$ ) we found that those in the northern lobe (with declination  $\delta \geq -42.57^\circ$ ) have radial velocity  $470 \pm 143 \text{ km s}^{-1}$  while those in the southern lobe (with  $\delta \leq -43.04^\circ$ ) have radial velocity  $580 \pm 148 \text{ km s}^{-1}$ . This seems to indicate that there is a regular rotation component at least of the innermost side of the Cen A lobes.

We would also like to mention that such mean temperature asymmetry method first applied to study the M31 galaxy (De Paolis et al. 2011, 2014) and applied here to the giant radio lobes of Cen A can become a conventional tool for studying of internal motions, especially towards

<sup>3</sup> AME should give an effect strongly frequency dependent in the CMB domain, too.

nearby galaxies, in the microwaves. As for the case of the SZ effect or e.g. for the Kolmogorov stochasticity parameter (Gurzadyan et al. (2009, 2014) and references therein), software for an automatic analysis by correlating galaxy surveys and CMB data may be developed.

The detected Cen A temperature asymmetry and especially its increase at small radii outline the picture of continuous ejections from a center which is rotating, and upon the increase of the size of the lobes, the effect of differential rotation becomes noticeable. Moreover, as one can see from Fig. 3, the temperature asymmetry within  $1.5^{\circ}$  tends to decrease from the 70 GHz band to the 143 GHz band, while it goes in the opposite directions at outer radii. This trend, if confirmed, seems to indicate that the dominant emission mechanism at CMB frequencies changes somewhere in between  $1.5^{\circ}$  and  $2.8^{\circ}$ , that is between about 92 kpc and 170 kpc.

It goes without saying that understanding the reason for the Cen A temperature asymmetry, that is if it is dominantly due to the ejection direction of the jets or to the rotation of the inner and outer lobes is of particular importance since it can throw light on the formation history and timescale evolution of this system and may allow us to get closer to the solution of the many unresolved questions about Cen A's giant radio lobes (see e.g. Eilek 2014). To this aim, we suggest to perform an analysis in the radio band, at 21 cm, similar to that done by Chemin et al. (2009) and Corbelli et al. (2010) for the disk of the M31 galaxy with the aim of tracking a radial velocity map of the outer regions of the Cen A system.

*Acknowledgements.* We acknowledge the use of *Planck*'s data in the Legacy Archive for Microwave Background Data Analysis (LAMBDA) and HEALPix (Górski et al. 2005) package. We thank L. Chemin for fruitful discussion. FDP, AAN and GI acknowledge the support by the INFN project TAsP and PJ acknowledges support from the Swiss National Science Foundation.

## References

- Bennett, C.L. 2003, ApJ, 148, 97  
 Bolton, J.G. 1948, Nature, 161, 141  
 Burigana, C., Davies, R.D., De Bernardis, P. et al. 2013, IJMPD, 22, id. 1330011  
 Burns, J.O., Feigelson, E.D. & Schreier, E.J. 1983, ApJ, 273, 128  
 Chemin, L., Carignan, C. & Foster, T. 2009, ApJ, 705, 1395  
 Clarke, D. A., Burns, J. O., and Norman, M. L. 1992, ApJ, 395, 444  
 Corbelli, E., Lorenzoni, S., Walterbor, R. et al. 2010, A&A, 511, id. A89  
 De Paolis, F., Ingrosso, G., Jetzer, Ph. et al. 1995, A&A, 299, 647  
 De Paolis, F., Gurzadyan, V.G., Ingrosso, G. et al. 2011, A&A, 534, id. L8  
 De Paolis, F., Gurzadyan, V.G., Nucita, A.A. et al. 2014, A&A, 565, id. L3  
 Eilek, J.A. 2014, New Journal of Physics 16, 045001  
 Górski, K. M., Hivon, E., Banday, A. J. et al. 2005, ApJ, 622, 759  
 Gurzadyan, V.G., Allahverdyan, A.E., Ghahramanyan, T., et al. 2009, A&A, 497, 343  
 Gurzadyan, V.G., Kashin, A.L., Khachatryan, H.G. et al. 2014, A&A, 566, A135  
 Hardcastle, M., Cheung, C., Feain, I. and Stawarz, L. 2009, MNRAS, 393, 1041  
 Harris, G.L.H., Rejkuba, M. and Harris, W.E. 2010, Publications of the Astronomical Society of Australia, 27, 457  
 Hui, X., Ford, H.C., Freeman, K.C. and Dopita, M.A. 1995, ApJ, 449, 592  
 Israel, F.P. 1998, AA&R, 8, 237  
 Karovska, M., Fabbiano, G., Nicastro, F. et al. 2002, ApJ, 577, 114  
 Marconi, A., Pastorini, G., Pacini, F. et al. 2006, A&A, 448, 921  
 Meier, D.L., Jauncey, D.L., Preston, R.A. et al. 1989, AJ, 98, 27

- Miville-Deschênes, M.A., Ysard, N., Lavabre, A. et al. 2008, A&A, 490, 1093  
 Neff, S. G., Eilek, J.A. and Owen, F.N. 2015, ApJ, 802, id. 88  
 Neumayer, N. 2010, Publications of the Astronomical Society of Australia, 27, 449  
 Peng, E.W. et al. 2004, ApJS, 150, 367  
 Planck Collaboration XII, 2014, A&A, 571, id.A12  
 Planck Collaboration I, 2015, A&A submitted; arXiv:1502.01582  
 Planck Collaboration XVI, 2015, A&A submitted; arXiv:1506.07135  
 Silge, J.D., Gebhardt, K., Bergmann, M. and Richstone, D. 2005, AJ, 130, 406  
 Tingay, S. J., Preston, R. A., and Jauncey, D. L. 2001, AJ, 122, 1697  
 Watson, R.A., Rebolo, R., Rubino-Martin, J.A. et al., 2005, ApJ, 624, L89  
 Woodley, K.A., Gómez, M., Harris, W.E., Geisler, D. and Harris, G.L.H. 2010, AJ, 139, 1871